LONG TERM CHARACTERIZATION OF THE ULYSSES REACTION CONTROL SYSTEM

Colin Goulding, Khee Chan
SciSys (Space & Defence) Ltd., Jet Propulsion Laboratory

Fernando Castro
Vega Group PLC, Jet Propulsion Laboratory

ABSTRACT*

The Ulysses spacecraft, launched in 1990, has performed in excess of 80,000 thruster firings to date. This paper details the results of a study to characterize the long term behavior of these thrusters as part of the Ulysses Reaction Control System (RCS). An overview of the Ulysses mission and spacecraft thermal environment are presented and the design of the spacecraft RCS is discussed. Throughout the course of the mission the spacecraft thermal environment has been a function of its stable predictable orbit, slowly decaying power source and the internal spacecraft configuration. The impact of the gradual cooling of the spacecraft on RCS performance is presented and discussed.

The vast majority of Ulysses thruster firings (>98%) have been performed on a single thruster, each in a similar fashion, allowing a detailed monitoring of in-flight performance. Thruster performance over the course of the mission, presented as thruster performance maps, is discussed and the use of this data for future planning by the spacecraft operations team presented. Finally a number of conclusions regarding current and future thruster performance are presented.

INTRODUCTION

The Ulysses mission is a collaborative effort of the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) to make the first-ever measurements of the unexplored region of space above the Sun's poles. The mission is unique as it adds another dimension to our understanding of the Solar System - exploring the heliosphere within a few astronomical units of the Sun over a full range of heliographic latitudes.

The spacecraft has been in continuous operation since it was launched on 6th October 1990 using the space shuttle Discovery. This came after a 4 year hiatus due to the space shuttle Challenger accident in 1986. Following launch, an Inertial Upper Stage (IUS) and Payload Assist Module (PAM) propelled Ulysses towards Jupiter. Passing over the north pole of Jupiter (at a closest distance of 6.3 Jupiter Radii) the spacecraft was slung out of the ecliptic plane and entered its operational orbit in February 1992.

Ulysses prime mission ended in 1995 following the observation of the suns poles at solar minimum. The mission was extended to cover a second set of polar passes in 2000 and 2001 to

* The work described here was performed by SciSys Ltd and VEGA Group PLC under contracts to the European Space Agency.

observe the poles during solar maximum. A further extension until March 2008 was recently approved which will enable the observation of the solar poles, once again at solar minimum, but with the Sun's magnetic field reversed.[1] A graphical representation of the spacecrafts third solar orbit is presented in Figure 1.

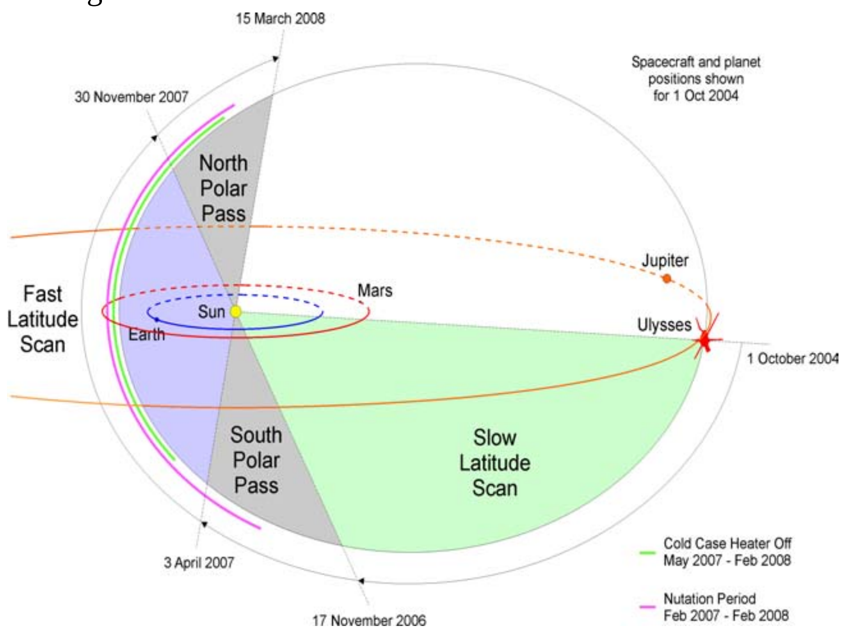


Figure 1: Ulysses Third Solar Orbit 2004-2008 [2]

Mission operations are being carried out by a joint multinational ESA/NASA team out of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. ESA provide the flight control team while the ground operations, data management and navigation teams are provided by NASA.

The Ulysses thermal environment is primarily a product of the two parameters detailed in Figure 2, namely the Heliocentric Range and Electrical Power Available. Ulysses' unique orbit, while stable, varies from 1.3 A.U. at perihelion to 5.4 A.U. at aphelion producing a solar flux varying from 45 to 1500 W/m^2. This thermal cycle has a periodicity of 6 years as the spacecraft repeats its orbit. Coupled with this thermal cycle is the ever decreasing power available to operate the spacecraft subsystems, instruments and heaters. This is due to the decay of the onboard radio-isotope thermoelectric generator (RTG) power output which has decreased from 285W of electrical power available at launch to 206W as of August 2004.

Electrical power generated onboard is used to power the spacecraft subsystems and payload with the remainder used to power four spacecraft heating circuits. Three of these circuits, namely the hot case, cold case and X-Wing heaters, are used to maintain the RCS at an operating temperature over the full range of heliocentric distances experienced by the spacecraft. The fourth circuit, which draws any power unused by the subsystems, payload and first three heating circuits, consists of a set of power dumpers (both internal and external) to control the spacecraft internal temperature.

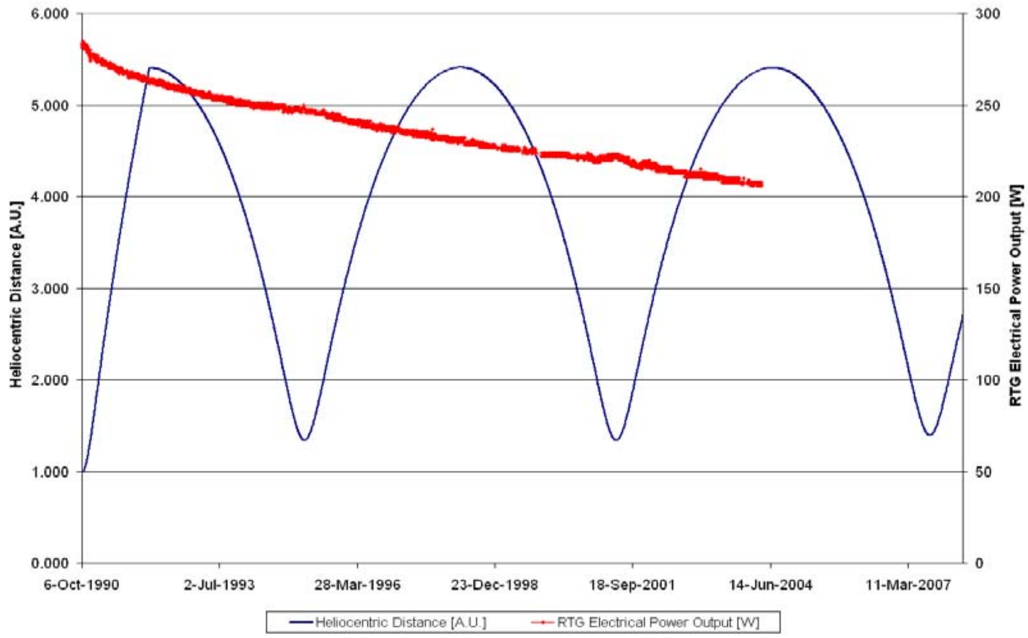


Figure 2: Ulysses Thermal Drivers

As the RTG electrical power output dropped below the prime mission requirement (237W), a payload power sharing plan was implemented to ensure that there is sufficient power to maintain the RCS at its operating temperature range. By splitting the payload into core (permanently on) and discretionary (cycled on and off) sections, power was made available to continue the mission until 2008, albeit at temperatures well below those experienced during the prime mission. The internal heating power and the thermal trends as experienced by the RCS pipe work inside the spacecraft are shown in Figure 3.

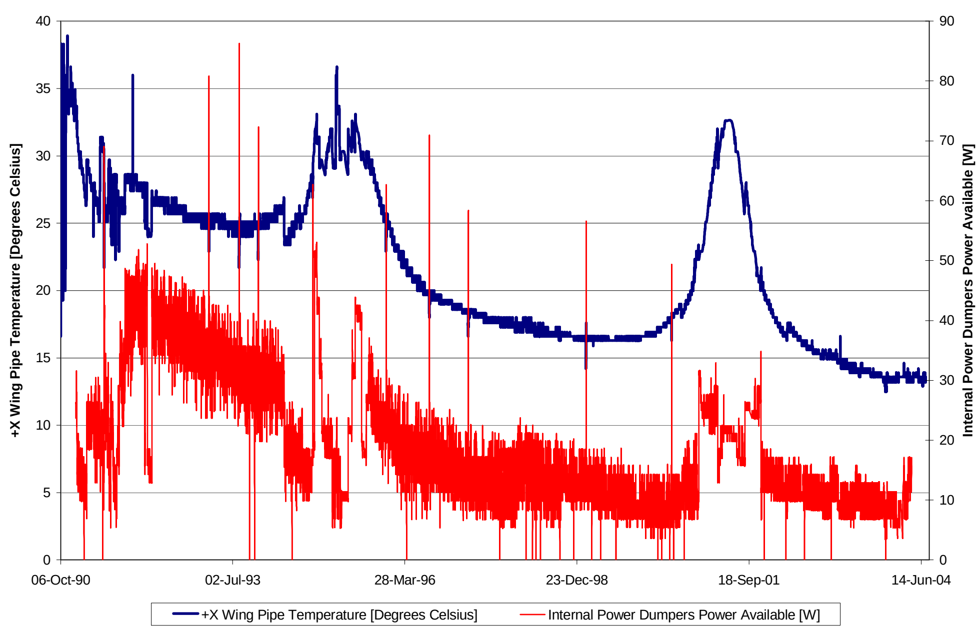


Figure 3: Ulysses Internal Heating Power Available and +X Wing Pipe Thermal Trends

ULYSSES REACTION CONTROL SYSTEM

The Ulysses RCS consists of a blow-down system using catalytic decomposition of monopropellant hydrazine fuel and is depicted with respect to the spacecraft body in Figure 4. Spin stabilized spacecraft conventionally use simple centrifuge propellant tanks mounted well away from the spin axis, but not so with Ulysses. Due to the low spin rate (5 rpm) and concerns associated with the interaction between propellant slosh and overall spacecraft dynamics the tank was mounted directly on the spin axis.[3]

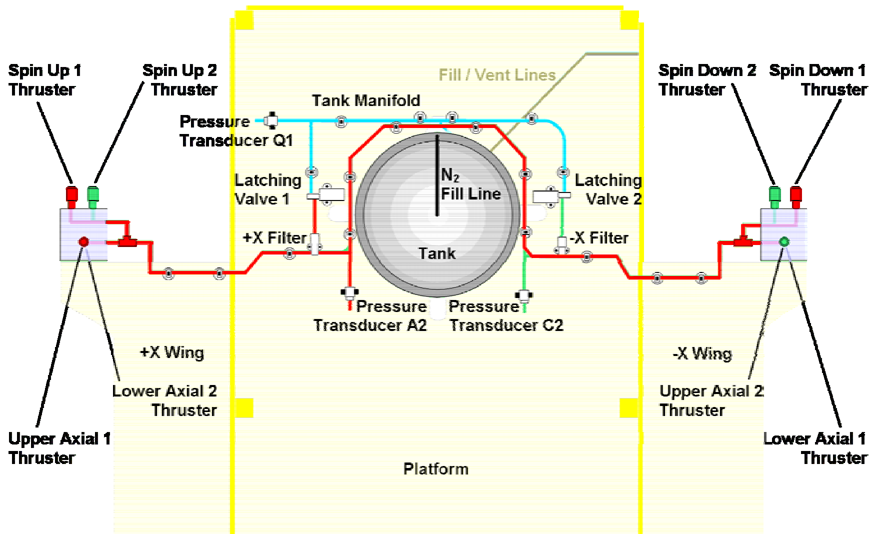


Figure 4: Spacecraft Upper Platform Schematic with RCS Details

The system consists of 8 thrusters arranged in two blocks of four: lower and upper axial, spin up and down. Each thruster was rated to produce 2 N @ 22 bar thrust at start-of-life and 0.6 N @ 5 bar at end-of-life.[4] The fuel tank feeds two identical fuel lines (shown schematically in Figure 5) each qualified to perform the complete mission profile. Total fuel load at launch was 33.5 kg and as of August 2004 there is approximately 7.8 kg remaining. By the end of the mission in March 2008, it is estimated that there will be 5 kg of fuel left. Each branch consists of a latching valve, protective filter, pressure transducer and one of each of the four thruster types. Both fuel lines feed both thruster blocks, located on opposite sides of the spacecraft providing for complete redundancy in operations. Following launch both branches were commissioned and calibrated and Branch 1 (as highlighted in Figure 5) selected as the prime unit. All routine operations have been conducted with the prime branch since its selection.

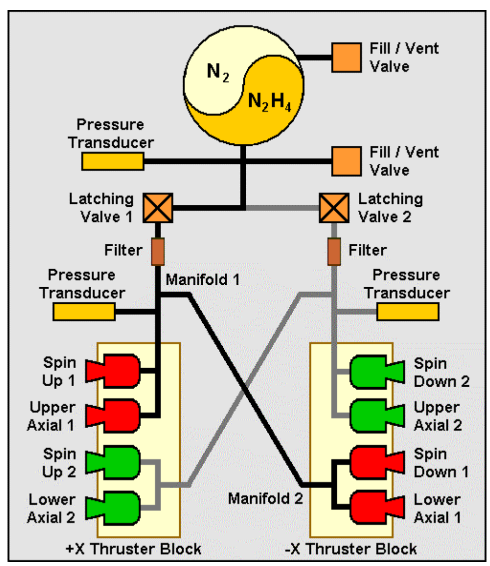
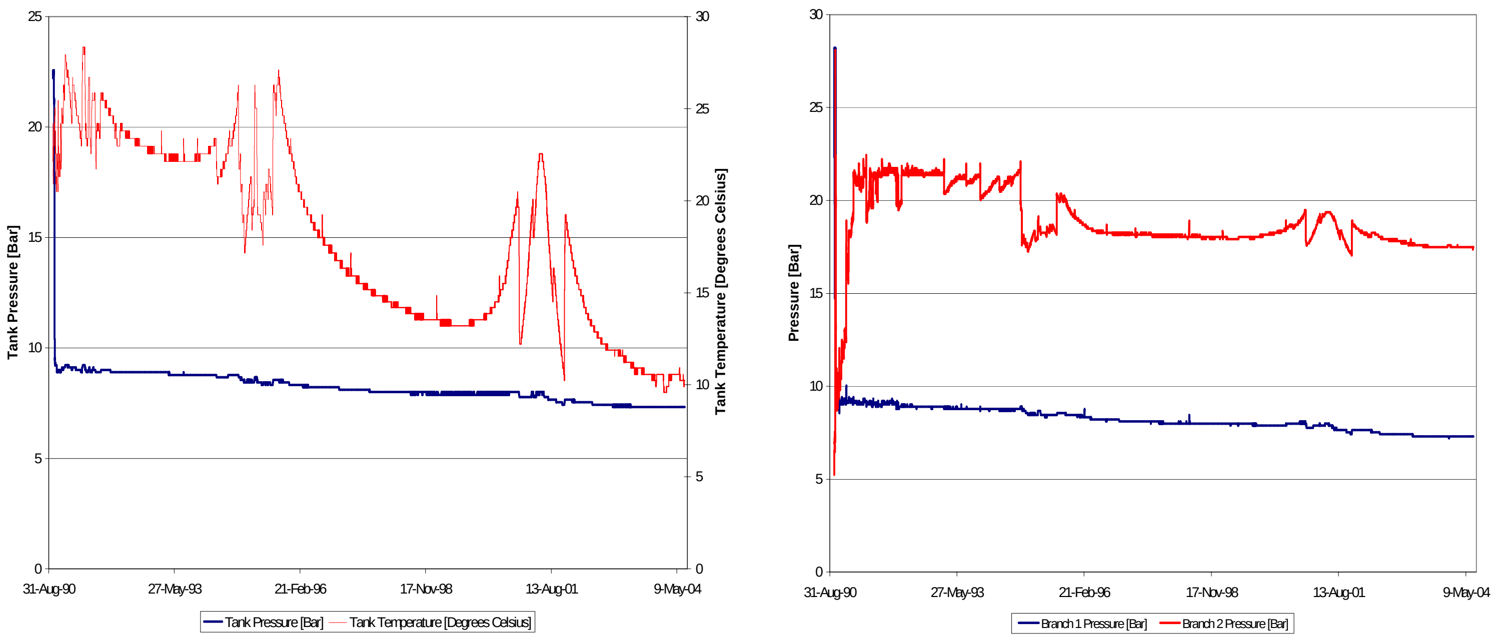


Figure 5: Schematic of Ulysses Reaction Control System

As detailed in Figure 5, provision was made for the monitoring of the propellant pressure both downstream and upstream of the latching valves. The results of this monitoring are presented in Figure 6 (a) and (b). The tank pressure and temperature profile for the duration of the mission may be seen in (a) while the pressures in both branch 1 and 2 may be seen in (b). En route to Jupiter, Ulysses executed three trajectory correction maneuvers (TCM) to ensure an accurate insertion into its operational orbit. The effect of these large maneuvers, occurring in October and November 1990 and July 1991, may be seen as pressure drops from 22 to 9.2 bar in RCS pressures in Figure 6. Following these TCMs the latching valve on branch 2 was closed and branch 1 has been used for all routine maneuvers to date.

The effect of using branch 1 for all routine maneuvers may be seen as a gradual pressure drop in both the tank and branch 1 pressure from a value of 9.2 in 1991 to 7.3 bar as of August 2004. Due to the use of a blow down pressurization system, pressure variations due to temperature variations are minimal in the tank and operational branch. Small variations in pressure are noticeable at perihelion in 1994/95 and 2000/01 but the overall trend is one of a gradual drop in pressure as the onboard fuel supplies decrease. The pressure readings for the redundant branch (Figure 6 (b)) show a greater influence of the spacecraft thermal environment due to the fuel currently being restricted to a sealed section of pipe work.



(a) (b)

Figure 6: Ulysses RCS Temperatures and Pressure Mission Profile

The same cyclical temperature pattern as seen for the platform in Figure 3 may be observed for the tank temperatures in Figure 6(a). A noticeable difference in the tank temperature profile is the large drop as the spacecraft approached perihelion in 1994/95 and 2000/01. As the solar incident radiation increases the spacecraft internal temperature rises rapidly. To ensure the propellant remains at a stable operating temperature, and in the course of the extended mission to provide more power for payload operations, the cold case heater circuit is switched off (releasing 24.9W) and the hot case circuit switched on (consuming 8.7W) causing a significant drop in RCS temperatures. As the spacecraft once again recedes from the Sun and the platform begins to cool the status of these circuits are once again reversed to maintain propellant temperatures within a stable operating range.

ULYSSES IN-FLIGHT RCS PERFORMANCE

The continuing excellent performance of the Ulysses RCS has been an integral component in the successful extension of the mission beyond its design lifetime. Since launch it has performed almost flawlessly on both branches across a range of operating conditions and in addition provided active nutation damping as a mission saving function. Anomalies associated with the RCS may be classified into three categories, namely

- **Plume Impingement**
  The effects of the Upper Axial 2 thruster impinging on a science instrument were noticed during the first TCM. This thruster is no longer used as it is an element of branch 2, which is currently the redundant branch, and there exist three other axial thrusters. This anomaly has not impacted spacecraft operations.

- **Spacecraft Safing Events**
  The latching valve on Ulysses requires a high transient current to open or close the valve. A number of spacecraft safing events have coincided with latch valve operations. For this reason, in addition to a concern regarding fatigue of the valves which arose following launch, the frequency of operation of the latch valves has been minimized without an impact on spacecraft operations.

- **Thruster Underperformance**
  The phenomenon of gas generation in hydrazine propulsion systems is well known and has been observed numerous times in the course of the Ulysses mission. [5] As the RCS is constantly being monitored and any use of the RCS is followed by detailed analysis this problem has also not impacted spacecraft operations.

Due to the importance of the continued nominal operation of the RCS and the identification of a number of anomalies, the operations team continuously perform both short and long term subsystem analysis. Following each manoeuvre an analysis of RCS performance is undertaken. Temperature profiles during the course of the manoeuvre are plotted and compared to that of previous maneuvers. Spacecraft orientation is calculated and compared to that predicted by simulations to verify nominal manoeuvre execution. In addition a detailed dataset is recorded and stored to enable long term trending.

The long term data set provided by Ulysses and used in the current work consists of 967 routine open loop slew maneuvers executed in an identical fashion over the course of 14 years. These manoeuvres are executed on a regular basis to keep the spacecraft at or close to Earth pointing in order to maintain downlink margin. Each manoeuvre detailed in the following analysis was executed on the LA1 thruster (unless stated otherwise) and fired with a pulse width of 3.2°, corresponding to a duration of 107 ms at a nominal spin rate of 5 rpm. Due to the constancy of operational use, the number of thruster firings, a commanded parameter, may be directly correlated to the fuel mass flow during a manoeuvre, which is not measured on-board. Data collected during Closed Loop CONSCAN operations, used to control spacecraft nutation during the period surrounding perihelion, has also been included which accounts for 1,322 non routine maneuvers. During these operations thermal and attitude data is not available and therefore the use of this data has been restricted to calculate the cumulative firings of the Lower Axial 1 (LA1) thruster. Two elements of RCS long term performance are discussed in more detail in the following sections, namely RCS health and efficiency, providing a long term characterization of the LA1 thruster. Both will first be presented below and their causes and effects on spacecraft operations then discussed.

RCS HEALTH TRENDS

The health of the RCS may be monitored over long periods of time using a set of onboard thermistors and pressure transducers (as shown in Figure 6). In characterization of long term performance, the temperature of the thruster/catalytic bed assembly is particularly relevant, giving an insight into both catalyst and thruster performance degradation.

For each routine manoeuvre the temperature profile of the catalyst bed, a telemetered parameter, is recorded with a typical temperature profile detailed in Figure 7. The temperature profile is composed of two distinct sections, one prior to thruster firing in which the 6W catalyst bed heaters are in operation, resulting in a slow heating to a holding temperature, and the second following thruster firing which produces a rapid rise in temperature due to the catalytic decomposition of hydrazine. The catalyst bed heaters are employed to prolong thruster cold start life and raise the temperature of the catalyst bed from spacecraft ambient conditions to a holding temperature in the region of 140°C. Over the course of the mission the length of time for which the catalyst bed heaters were in operation prior to thruster firing has varied due to onboard power requirements. During the first year of operation the heaters were permanently on while a value of close to 80 minutes has been used since. The rapid rise in temperature due to thruster firing is dependent on the amount of fuel flowing over the catalyst beds and can be seen to continue to increase as the thruster continues to fire, therefore a larger manoeuvre will produce a greater maximum temperature than a shorter one.

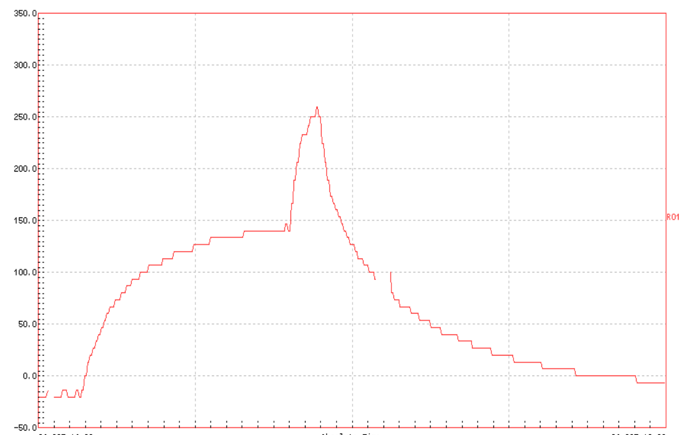


Figure 7: Typical Catalyst Bed Temperature Profile during Manoeuvre

Figure 8 shows the RCS mission long trends for the manoeuvre temperature profile. For the current analysis the data has been subdivided into years of operation and the temperature rise from catalyst bed heating to manoeuvre completion plotted against the mass flow (represented in

Figure 8 as the number of thruster firings executed during the manoeuvre). In each year a curve is fitted to the data representing a line of best fit with the length of the line representing the maximum and minimum number of pulses for a manoeuvre in any given year. This produces a characterization map for the LA1 thruster/catalyst bed performance over the course of the mission. Each years performance follows a very similar trend with the temperature increasing for an increasing number of pulses. A degradation of system performance may be seen as the temperature rise for any number of pulses decreases over time. In addition a trend may be observed following periods of nutation control in 1995 and 2000 with an increased rate of system performance degradation being observed post nutation.

The period of use of the Upper Axial 1 (UA1) thruster in 2002/03 is also represented as a measure of a similar thruster/catalytic bed system which did not undergo constant use. The performance difference between UA1 and LA1 in this time period is in the order of a 40°C difference for any given number of pulses. It is interesting to note that while the UA1 thruster has had a similar number of firings to that of LA1 in 1992 its performance is significantly reduced. This may be due to a reduced system pressure and temperature in branch 1 of the RCS. If the LA1 thruster performance continues to degrade switching to UA1 may provide system performance similar to that experienced with LA1 in the late 1990s.

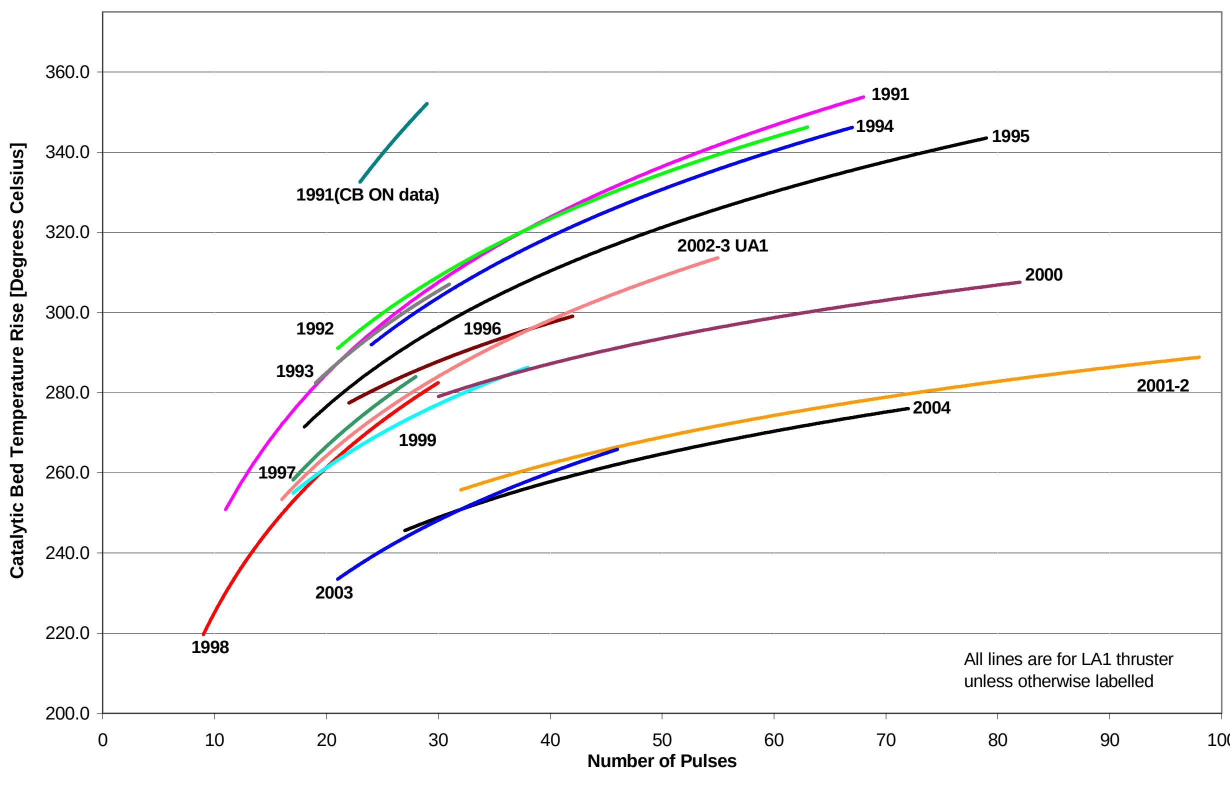


Figure 8: Ulysses RCS Performance Map

RCS EFFICIENCY TRENDS

A second, perhaps more critical, measurement of RCS performance is the efficiency with which it performs its function, in this case the slew length achieved per pulse fired. Figure 9 details the efficiency of the RCS system over the course of the mission. In addition the cumulative number of LA1 thruster firings is also represented.

The dataset has a large spread, representing the uncertainties of the actual slew length and the variability of performance with respect to the length of the manoeuvre. The uncertainties in the slew length arise from the attitude measurement uncertainties during pre and post manoeuvre attitude determination. Additionally each manoeuvre has a different number of pulses based on the manoeuvre requirements. A greater number of pulses generates a greater increase in temperature, as detailed in Figure 8, and overall manoeuvre efficiency increases as the number of pulses increases. A number of outliers, particularly in 1995 and 1996, are due to aborted maneuvers as the spacecraft entered safe mode following a latching valve operation.

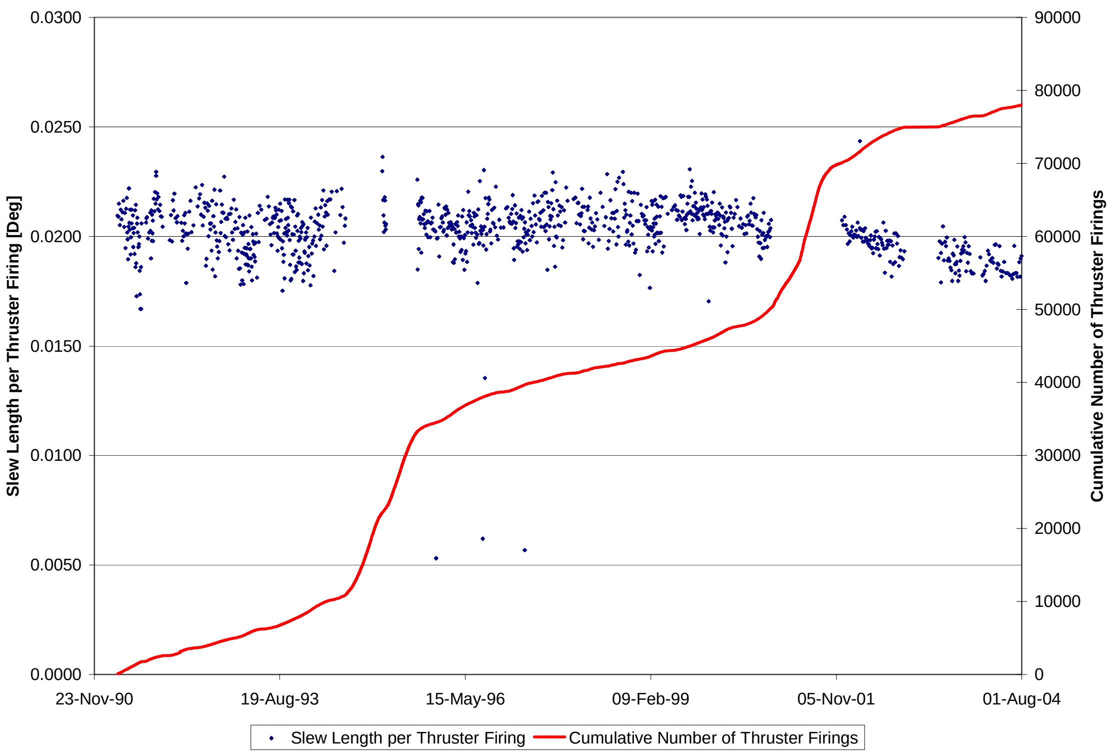


Figure 9: Ulysses Thruster Efficiency and Cumulative Number of Firings

Three distinct periods without routine maneuvers may be noted from Figure 9, namely 1994/95, 2000/01 and a smaller period in 2003. During 1994/95 and 2000/01 closed loop CONSCAN was used to control the Ulysses nutation anomaly and no attitude data is available. It can also be noted that during this time the number of thruster firings increases dramatically due to the constant firing of thrusters in order to dampen spacecraft nutation. During 2003 a number of manoeuvres were performed with the UA1 thruster for calibration purposes.

Although the data has a large spread, a definite fall off in efficiency may be observed following the period of nutation in 2000/01 and a cumulative number of 70,000 thruster firings.

DISCUSSION OF THRUSTER PERFORMANCE DEGRADATION

The Ulysses RCS performance as presented in Figure 8 and Figure 9 provides a clear picture of RCS degradation over time. While the performance of the LA1 thruster/catalyst bed system, detailed in Figure 8, has shown a steady decrease over time this has not affected thruster efficiency until 70,000 thruster firings were reached in 2001. The relationship between these trends and its corresponding impact on spacecraft operations may be attributed to a number of factors, each of which are addressed in the following sections.

THERMAL AND PRESSURE EFFECTS

Each individual thruster is rated to produce 2 N at 22 Bar thrust and down to 0.6 N at 5 Bar at end of life. The pressure trends for the mission, as detailed in Figure 6, show the large decrease in system pressure due to the TCMs followed by a gradual decrease in the years following from 9.5 Bar to a current value of 7.2 Bar. While a gradual mission long decrease in performance is shown year on year in the system performance map, in Figure 8, the same expected trend is not seen in the efficiency map, Figure 9. The expected fall off in thruster efficiency is only observed clearly in latter years following the second period of Ulysses nutation. It is therefore believed that the system pressure has not been a driving function in the decrease of system performance over the course of the mission.

The cyclical temperature patterns of the spacecraft platform, seen in RCS temperatures in Figure 6, are not present in Figure 8 and Figure 9. Figure 8 has been normalized with respect to the temperature of the catalyst bed prior to manoeuvre execution and shows a constant degradation of system performance while Figure 9 does not exhibit any cyclical effects. The decoupling of RCS performance from spacecraft temperature is due to the use of a blow down system in which the branch and tank pressure are not greatly influenced by system temperature, as seen in Figure 6 (a) and (b). The constant decrease in the pressure seen in these plots is therefore purely a function of the increase in ulleage volume as fuel is consumed.

It may be speculated that after the decrease in system pressure following the nutation period in 2001 that the Ulysses RCS has moved to a regime in which the system pressure is of greater influence on RCS performance. If this is the case a further degradation of performance will be experienced over the coming years as the system pressure decreases towards its end of life value. In the event of tank and manifold pressure driving the thruster performance then there is little the operations team may do to prevent further degradation regardless of which thruster is used. The opening of the latching valve for branch 2 is a possibility to increase tank and branch 1 system pressures or the use of branch 2 without the opening of its latch valve to make use of its higher, more temperature dependent pressure.

RCS MEASUREMENT ERROR EFFECTS

While each manoeuvre on the LA1 thruster has been performed in a similar fashion the efficiency of any given manoeuvre was seen to exhibit large variations. A difficult element to quantify in the measurement of Ulysses telemetered data is the performance of the RCS measurement system itself. Over the course of the mission the ground processing of onboard thermistors and transducer outputs has remained at its initial calibrated level. As the mission lifetime was extended the reduced temperatures have driven the thermistors to regions below their intended operating regime. In addition the thermistors measuring higher end temperatures have been subjected to repeated cycling between the now very cold ambient temperatures and the peaks associated with thruster firings.

A further impact on the collection of telemetered data outside its initial operating limits is the decrease in data resolution. As the spacecraft ambient temperature has reached temperatures well below its initial design limits the accuracy to which the temperatures and pressures are measured decreases.

It is believed that neither of these measurement error effects influence the data presented in the current study. As it is essential to maintain the propellant above its freezing temperature the thermistors associated with the RCS have all been maintained at temperatures above that seen for the rest of the spacecraft platform. While thermistor lifetime performance degradation is a possibility its effect is difficult, if not impossible, to quantify for the Ulysses measurement system.

SYSTEM DEGRADATION EFFECTS

During the course of the current study an attempt has been made to investigate clear patterns of system degradation to aid with future operations planning. An attempt has been made to quantify other influencing effects such as pressure and temperature decreases and measurement error which also influence system degradation.

While the Ulysses RCS has performed remarkably well since launch as detailed in Figure 9 a decrease in efficiency has been observed in recent years. While this may be due to a decrease in system pressure, it should also be noted that the LA1 thruster/catalyst bed system has performed in excess of 70,000 firings prior to a drop in performance. Fatigue effects of the thruster assembly and catalyst bed may start to become more pronounced over the coming 4 years. If this is the case then the option of utilizing the UA1 thruster may be recommended or a change from the prime RCS branch 1 to branch 2.

INFLUENCE ON FUTURE OPERATIONS

If the degradation of the system were to significantly affect Ulysses operations a testing campaign across the branch 1 thrusters to investigate both pressure, temperature and system degradation effects may provide useful information with regard to the function driving RCS performance degradation. It is likely that a combination of all of the above factors is responsible for the recent performance degradation and the identification of the prime effect would allow the operations team to make informed decisions with regards to RCS configuration. Extrapolating the recent downward efficiency trend the increase in fuel required over the coming years may be calculated. Ulysses has sufficient fuel available to enable it to complete its current mission until the planned end date in 2008 even if the performance of the RCS degrades at a rate double that seen in Figure 9.

The performance of the RCS will continue to be monitored by the operations team over the coming years and compared to lifelong system performance. Operational decisions regarding the configuration of the RCS may be made based on the trends observed in this data ensuring Ulysses can continue to provide its excellent service to the science community until end of mission in 2008.

CONCLUSIONS

The operational performance of Ulysses RCS has been described in detail from launch in 1990 to August 2004. The RCS has performed remarkably well through the course of the prime mission and for the 9 years of extended operation. Although performance degradation of the LA1 thruster has been occurring over time it did not impact the thruster efficiency until a figure of 70,000 firings were reached in 2001.

This decrease in efficiency will result in an increased use of fuel per unit slew length for future maneuvers with a further degradation predicated over the next 4 years of operation. This period will also include fuel hungry nutation operations in which the vast majority of Ulysses thruster firings take place. This will not impact the operation of the spacecraft owing to sufficient fuel reserves. In the event of a more rapid degradation being observed the second axial thruster on branch one may be used or the spacecraft team may elect to move from the prime RCS branch and put the backup branch two into operation.

The collection of a detailed dataset over the course of the Ulysses mission has provided a unique dataset to examine and characterize RCS performance. Constant monitoring of trends over a number of years through the use of performance and efficiency maps allows the spacecraft team to make informed decisions regarding the operation of a system well beyond its design life. The impact of these decisions has directly influenced the success of Ulysses in achieving its mission goals from 1990 to 2004 and should continue to do so to the end of operational life in 2008.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts of the Ulysses operations team over the course of the mission, and in particular Andy McGarry, for the creation and maintenance of a detailed RCS dataset. The authors also acknowledge the support of Nigel Angold, Ulysses Spacecraft Operations Manager, in our research of this topic and the European Space Agency, Scisys (Space and Defense) Ltd. and VEGA Group PLC for their support and funding of this work.

REFERENCES

1. Angold N., Beech P., Brymer B., Castro F., Hodges M., McGarry A., "2004 – 2008 Ulysses Extension Study", report for Ulysses Science Working Team Meeting, October 2002.

2. McGarry A., Castro F., Hodges M., "Increasing Science with Diminishing Resources - Extending the Ulysses Mission to 2008", SpaceOps 2004, Montreal, May 2004

3. McGarry A., Berry W., Parker D., "Inflight Performance of the Ulysses Reaction Control System", 2nd European Space Propulsion Conference, Noordwijk, The Netherlands, 27-29 May, 1997

4. European Space Agency, "The Ulysses Data Book", ESA-BR-65, June 1990

5. American military specification MIL-P-26536D: High Purity Hydrazine.

6. Chan K., Paredes E.S., Ryne M.S., "Ulysses Attitude and Orbit Operations: 13+ Years of International Cooperation", SpaceOps 2004, Montreal, May 2004.

CONTACT

Questions or requests for additional information may be directed to:

Colin Goulding,

Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 264-114, Pasadena, CA 91109, USA

e-mail: colin.goulding@jpl.nasa.gov